Dual-Arm Long-Reach Manipulators: Noncontact Motion Control Strategies

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Abstract

This work reports progress on a long-reach manipulator project. The original single-arm manipulator was complemented with an identical second arm. We introduce several noncontact motion control strategies which are based on the reaction null space concept developed earlier. Experimental verification of disturbance compensation control via a single arm, and via the two arms while holding an object, is done. Also, motion feasibility on reactionless paths for a closed kinematic chain, including the two arms and the object, is examined.

1. Introduction

The concept of a so-called macro-micro manipulator system has been introduced by Sharon and Hardt [1]. This concept has evolved throughout the years to meet mainly two types of application demands: nuclear waste cleanup [2] and space robotics [3]. Often, the manipulator systems are called long-reach manipulators (LRM).

Most of the experimental work done so far focuses on a single small arm mounted on a single large arm. We note, however, that LRM with a dual- or multiple-arm micro subsystem will play an important role in the near future. One example is the Canadian SSRMS/SPDM project. Another example, already operational, is the Japanese hot-line maintenance manipulator [4].

The control of a LRM is quite challenging due to the presence of dynamic coupling between the two substructures. A literature survey shows that for single-arm LRM three main control subtasks can be identified: (1) base vibration suppression control, (2) design of control inputs that induce minimum vibrations [5], and (3) end-point control in the presence of vibrations [6], [7].

In a previous work, we applied the so-called reaction null space concept to analyze single-arm LRM and to design proper control laws [8], [9]. Via the reaction null space, we decompose the joint space such that dynamic decoupling between the macro and the micro subsystems is achieved. We have implemented the method into a single-arm experimental LRM called TREP [9].

The aim of this work is to report further progress on our research. We have added a second arm to the flexible base of TREP. This enables new control strategies to be designed and verified.

2. Notation and Background

We consider a dual-arm LRM; the general case of a multi-arm LRM is easily derivable from the model below. We will refer to the two arms as “upper” and “lower” arm, and use subscripts u and l in the notation. For example, the number of joints will be denoted as nu and nl, respectively. The system dynamics can be written in the following form:

\[
\begin{bmatrix}
H_{b}(x_{b},\theta) & H_{bl}(x_{b},\theta) \\
H_{bl}^{T}(x_{b},\theta) & H_{ll}(x_{l},\theta)
\end{bmatrix}
\begin{bmatrix}
x_{b} \\
\dot{\theta}
\end{bmatrix}
+ \begin{bmatrix}
K_{b}x_{b} \\
0
\end{bmatrix}
+ \begin{bmatrix}
c_{b}(x_{l},x_{b},\theta,\dot{\theta}) \\
c_{m}(x_{l},x_{b},\dot{\theta})
\end{bmatrix}
= \begin{bmatrix}
0 \\
\tau
\end{bmatrix},
\]

where \(x_{b} \in \mathbb{R}^{m}\) denotes the positional and orientational deflection of the base with respect to the inertial frame, \(\theta \in \mathbb{R}^{n} (n = n_{u} + n_{l})\) stands for the generalized coordinates of the two arms, \(H_{b}\) and \(K_{b} \in \mathbb{R}^{m \times m}\) denote base inertia, and stiffness, re-
respectively. \( \mathbf{H}_m \in \mathbb{R}^{n \times n} \) is the block-diagonal inertia matrix of the two arms. \( \mathbf{H}_{bm} \in \mathbb{R}^{m \times n} \) denotes the so-called inertia coupling matrix. \( c_b \) and \( c_m \) are velocity-dependent nonlinear terms, and \( \tau \in \mathbb{R}^n \) is the joint torque. We do not consider external forces here, including gravity forces, since we focus only on noncontact tasks in micro gravity environment.

We focus on two main control subtasks: (1) active vibration suppression at a point where the arms are stationary, and (2) initializing motion such that no vibrations in the base occur (reactionless motion control subtask). In both cases, we can make two important assumptions: first, that nonlinear couplings due to base deflection can be ignored, and second, that inertia submatrices are functions of the joint variables only. Thus, from the upper part of the above equation we obtain the following expression for the base dynamics (i.e. force balance at the base):

\[
\mathcal{F} = \mathbf{H}_b \ddot{x}_b + \mathbf{H}_{bm} \ddot{\theta} + c_b(\theta, \dot{\theta}) + \mathbf{K}_b x_b = 0. \tag{2}
\]

In case of the vibration suppression control subtask, we can ignore also the nonlinear term \( c_b(\theta, \dot{\theta}) \) [10]. Then, the goal is to find a proper manipulator control law that would introduce the necessary damping into the system. This can be achieved with the control acceleration [10]:

\[
\ddot{\theta}_b = \mathbf{H}^+_{bm} \mathbf{H}_b \mathbf{G}_b \ddot{x}_b, \tag{3}
\]

where \( \mathbf{G}_b \) is a gain, \( \dot{x}_b \) is a feedback variable (measured e.g. by strain gauges), and \( \mathbf{H}^+_{bm} \in \mathbb{R}^{m \times n} \) denotes the Moore-Penrose generalized inverse of the inertia coupling matrix.

In case of the reactionless motion control subtask, Equation (2) can be rewritten as

\[
\mathbf{H}_b \ddot{x}_b + K_b x_b = -\mathbf{H}_{bm} \ddot{\theta} - \dot{\mathbf{H}}_{bm} \dot{\theta}. \tag{4}
\]

The specific motion of the manipulator that maintains base equilibrium, i.e.

\[
\mathbf{H}_{bm} \ddot{\theta} + \dot{\mathbf{H}}_{bm} \dot{\theta} = 0 \tag{5}
\]

we call reactionless manipulator motion. The above equation can be integrated to:

\[
\mathcal{L}(t) = \mathcal{L}(t_0) + \mathbf{C}_{bm} \dot{\theta}(t), \quad t \geq t_0, \tag{6}
\]

where \( \mathcal{L} = \mathcal{L}(t_0) = \mathbf{H}_{bm} \dot{\theta}(t_0) \) is the integration constant. This integral has been called the coupling momentum [8].

From Equations (5) and (6) it is apparent that the arms will not induce any reaction to the base if and only if the coupling momentum is conserved (\( \mathcal{L} = \text{const} \Leftrightarrow \mathcal{F} = 0 \)). Let us assume that \( n > m \) holds. Then, solving Equations (5) and (6) under the above conditions, we obtain:

\[
\ddot{\theta}_c = -\mathbf{H}^+_{bm} \mathbf{H}_{bm} \ddot{\theta} + (\mathbf{E} - \mathbf{H}^+_{bm} \mathbf{H}_{bm}) \mathcal{L} \tag{7}
\]

and

\[
\dot{\mathcal{L}}_0 = \mathbf{H}^+_{bm} \mathcal{L}_0 + (\mathbf{E} - \mathbf{H}^+_{bm} \mathbf{H}_{bm}) \mathcal{L} \tag{8}
\]

for joint acceleration and joint velocity, respectively. Therefore, \( \mathbf{E} \in \mathbb{R}^{n \times n} \) stands for the unit matrix and \( \mathcal{L} \in \mathbb{R}^n \) is arbitrary. The expression \( \mathbf{P}_{RNS} \equiv (\mathbf{E} - \mathbf{H}^+_{bm} \mathbf{H}_{bm}) \) denotes a projector onto the null space of the inertia coupling matrix. This null space is called the reaction null-space.

The reaction null space exists whenever the condition \( n > m \) is met. Equation (7) shows that the arms can accelerate within this null space, from rest, without disturbing the base equilibrium. The zero initial coupling momentum will be then necessarily conserved. Below we will consider two typical cases of single-arm operation and dual arm-operation. In the former case, one of the arms is totally free: all its degrees of freedom can be used to constitute the reaction null space. In the latter case, however, this is not so: the reaction null space shrinks significantly and may even disappear.

3. The Experimental LRM TREP-II

We have introduced our experimental single-arm LRM called TREP in [9]. It consists of a small planar 2R rigid link manipulator attached to the free end of a flexible double beam representing an elastic base. Due to the specific design, we can assume that the base deflects only from the longitudinal axis. In other words, the reaction moment and the reaction force component along the longitudinal axis of the base can be neglected as a disturbance. The force/torque sensor is used to measure the three reaction components in the flexible base plane. The strain gauge signal is used for feedback base deflection control, when needed. Meanwhile, we have attached a second small arm which is identical to the first one (see Figure 1).

The system model is depicted in Figure 2. We consider just the reaction force component along the low stiffness direction (the \( z \) axis of the elastic-base coordinate frame). This means that \( m = 1 \). Since each arm has two motors (\( n = 4 \)), the reaction null space is three-dimensional.

To derive the reaction null space, we need the inertia coupling matrix. In our case \( \mathbf{H}_{bm} \) is \( 3 \times 4 \). Since we are interested in the reaction force only along the low-stiffness \( x \) axis, we will apply the selective reaction null space procedure [8]. Essentially, this will reduce

Let us consider the case when a dextrous motion control task is assigned to one of the arms, say, to the upper one. The inertial coupling between the lower arm and the macro-base may be utilized to minimize disturbances. From Equation (10) it is straightforward to derive the joint velocity of the lower arm which would maintain the zero-reaction condition, i.e. \( \mathcal{L} = 0 \). We have:

\[
\dot{\theta}_l = -\dot{\mathbf{H}}_{bml}^+ \dot{\mathbf{H}}_{bmu} \dot{\theta}_u + (E - \dot{\mathbf{H}}_{bml}^+ \dot{\mathbf{H}}_{bml}) \zeta. \tag{11}
\]

The expression \((E - \dot{\mathbf{H}}_{bml}^+ \dot{\mathbf{H}}_{bml}) \zeta\) shows that the joint velocity we are looking for constitutes a set. This is explained with the fact that the arm has more degrees of freedom than necessary (for inertial coupling along \( x \)). Choosing the arbitrary vector \( \zeta = 0 \), we obtain a joint velocity vector of minimum norm, which is due to a well-known property of the pseudoinverse. Thus, we can guarantee that the lower arm will compensate disturbances in a locally optimal way, with minimum kinetic energy.

![Control block diagram for the lower-arm disturbance compensation strategy](image)

Using Equation (11), we designed the feedback controller shown in Figure 3. The following experiment was conducted. The two arms were placed in the same initial configuration \([90^\circ, 0^\circ]^T\). The final configuration of the upper arm was assigned as \(\theta_u = [180^\circ, -90^\circ]^T\). Between the initial and final configurations, the upper arm reference trajectory was determined via a fifth-order polynomial, with total time of 1 s. The feedback gain matrix \(K_p = \text{diag} [100 \ 100 \ 100] \text{s}^{-1}\). Figure 4 shows the motion of the two arms, Figure 5 displays data for reference and feedback positions, as well as the disturbance force and the deflection of the base. It is clearly seen that the arms track their reference trajectories accurately, and as a consequence, the reaction force along \( x \) and the deflection are minimized. For comparison, Figure 6 shows the reaction forces and the deflection in case the lower arm remains stationary.
Figure 4. Upper arm tracks a desired path; lower arm compensates the disturbances.

Figure 5. Disturbance compensation experiment.

5. Dual-Arm Motion Control Strategies

We will consider the case when the two arms hold an object. Two motion strategies will be proposed: (1) reactionless motion control while carrying the object, and (2) vibration suppression while holding the object.

5.1. Reactionless Motion

We simulate the presence of an object by imposing the constraint

\[ \mathbf{r}_{ue} - \mathbf{r}_{le} = \text{const} \]  \hspace{1cm} (12)

Figure 6. Experiment without disturbance compensation.

where \( \mathbf{r}_{ue} \) and \( \mathbf{r}_{le} \) denotes the end-tip position of the upper and lower arm, respectively. This constraint ensures pure translational motion of the object. Differentiating with respect to time, we obtain

\[ \dot{\mathbf{r}}_{ue} - \dot{\mathbf{r}}_{le} = \mathbf{B}(\theta)\dot{\theta} = 0 \]  \hspace{1cm} (13)

where \( \mathbf{B}(\theta) \) is a \( 2 \times 2 \) matrix. Adjoining the last equation to the coupling momentum equation, we obtain

\[ \begin{bmatrix} \mathbf{H}_{bm} \\ \mathbf{B} \end{bmatrix} \dot{\theta} = 0. \]  \hspace{1cm} (14)

Denote the composite matrix above as \( \mathbf{H}_{bm,B} \). The dimension is \( 3 \times 4 \) which implies the existence of a one-dimensional null space. Thus,

\[ \dot{\theta} = (\mathbf{E} - \mathbf{H}_{bm,B}^{-1} \mathbf{H}_{bm,B}) \zeta. \]  \hspace{1cm} (15)

The matrix operator \( (\mathbf{E} - \mathbf{H}_{bm,B}^{-1} \mathbf{H}_{bm,B}) \) determines a one-dimensional distribution in the four-dimensional common joint space of the two arms. This distribution is integrable. Upon its integration, we obtain the set of reactionless paths of the LRM holding a specific object. These paths can be projected onto the workspace. Figure 7 shows the paths of the center point (CP) of an object of 60 mm length. The initial configuration of the arms is always such that the vector \( \mathbf{r}_{ue} - \mathbf{r}_{le} \) is parallel to the \( x \) axis.

We performed the following reactionless motion control experiment. The initial position of the object CP was \((-0.05, 0.05)\) m. The initial arm configuration was \( \theta = [39^\circ \ 149^\circ \ 209^\circ \ -124^\circ]^T \). Figure 8 shows the initial configuration of the arms with the object, and the path of the object CP. Figure 9 shows the reaction forces and the distance between the end-tips, calculated from feedback data. It is apparent that both constraints are maintained while moving the arms.

5.2. Vibration Suppression

Instead of the constraint Equation (12), we consider now

\[ \| \mathbf{r}_{ue} - \mathbf{r}_{le} \| = \text{const}. \]  \hspace{1cm} (16)
with respect to time, we obtain
\[ \frac{d}{dt} \| \mathbf{r}_{ua} - \mathbf{r}_{le} \| = A(\theta) \dot{\theta} = 0. \] (17)

Matrix \( A(\theta) \) above is \( 1 \times 4 \).

For vibration suppression, we have to consider the base dynamics. In the case of TREP, base dynamics are written as a scalar equation. We differentiate the object constraint Equation (17) once more with respect to time, and adjoin it to the base dynamics to obtain:
\[
\begin{bmatrix}
\dot{H}_{bm}^A \\
A
\end{bmatrix} \dot{\theta} + \begin{bmatrix}
H_b \\
0
\end{bmatrix} \ddot{x}_b + \begin{bmatrix}
C_b \\
A\theta
\end{bmatrix} + \begin{bmatrix}
k_b \\
0
\end{bmatrix} x_b = \begin{bmatrix}
0 \\
0
\end{bmatrix}.
\] (18)

We rewrite the above equation in a more compact form:
\[
\dot{H}_{bmA}^+ \dot{\theta} + H_{bA} \ddot{x}_b + C_{bA} + K_{bA} x_b = 0.
\] (19)

Then, under the assumption that \( C_{bA} \) is small, we can apply a control law as in Equation (3):
\[
\ddot{\theta}_v = \dot{H}_{bmA}^+ H_{bA} G_v \ddot{x}_b,
\] (20)

where \( G_v = \begin{bmatrix} G_v & 0 \end{bmatrix}^T \), \( G_v \) denoting a vibration suppression feedback gain.

As the motors of our experimental LRM are velocity-driven, we integrate the above control approximately, under the assumption that \( \dot{H}_{bmA} \) and \( H_{bA} \) is constant. The control scheme used in the following vibration suppression experiment is depicted in Figure 10. We must strongly emphasize that decoupling of the vibration control loop from the path tracking loop is possible only for reactionless paths. This should be clear from the fact that the vibration suppression component comes from the orthogonal complement of the reaction null space. In this case, the design of the control gains is not critical. For any other paths, there is a coupling, and careful design of the gains is necessary.

The experiment we performed is described as follows. The initial configuration is stationary: \( \theta = [50^\circ \ 60^\circ \ 130^\circ \ -60^\circ]^T \). The reference path is also stationary and equal to the initial configuration. An arbitrary external disturbance impulse is applied which initializes the vibration. Under these conditions, the two loops are not decoupled. Therefore, we have to decrease the position feedback gain, as compared to the previous experiments. We used \( K_p = \text{diag} \{ 50, 50, 50, 50 \} \text{ s}^{-1} \). \( G_v \) was chosen
to be 20 s\(^{-1}\). The results of the experiment are shown in Figure 11. It is clearly seen that vibration suppression is successfully done and the reference configuration is attained. In addition, the object constraint is maintained (data not shown).

Figure 11. Vibration suppression experiment.

6. Conclusions

This work has shown how the reaction null space concept can be applied to a dual-arm LRM. We introduced several noncontact motion control strategies including disturbance compensation via a single arm, and via the two arms while holding an object. We have shown also the existence of reactionless paths for a closed kinematic loop including the two arms and the object. These paths might be useful as supporting elements in path planning strategies and work placement analysis. Although the experimental results have been derived with a relatively simple planar system, the theoretical base is general.

Acknowledgments

The support through the Ippan C Research Project 07805027 Grand-in-Aid for Scientific Research from the Ministry of Education, Science and Culture of Japan is acknowledged.

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